Corrosion, Environmental Degradation and Surface Engineering
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Lecture – 13
Corrosion – Part II

Welcome to Lecture 10 of this course on corrosion, environmental degradation, and surface engineering. The title of the 10th lecture is Surface Degradation Mechanism Due to Corrosion Action. It is a second part because in the 9th lecture we also covered corrosion action. And then what we realized in the previous lecture was that even the materials are good, but if there is some sort of impurity, it will increase the chances of corrosion. And on this slide, I am just repeating the lecture on the 9th. In this case, there are 3 figures: A, B, and C.

In the case of A, what we have done is create a copper sheet, and on top of that, there is some sort of flux of graphene. Now, in this flux, we are able to show some sort of discontinuity or some sort of passage that is available for the impurities or for the galvanic corrosion. So, grain boundaries have been shown in this case to be misaligned. So, graphene has been shown to be adsorbed on the water molecule, or oxygen, as shown here.

There are some vacancies. So, and moreover, there are wrinkles too. Any of this kind of discontinuity, or maybe say that there is some effect that can be brought by the discontinuity, will increase the corrosion rate. And that has been shown here in figure A. There are 2 sides, we say the C and B, and the B has been expanded, and they are shown in a zoom form or magnified form. The B is the $1\mu m$ scale, while the C is also a $1\mu m$ scale.

What has been shown in B is the corrosion of a copper, while in C it has been shown the patch wherever the graphene was residing or was kept on the top surface of the copper. So, if you bring some sort of impurity, that will give us some path for the electrolyte or for the conductant path, which will create corrosion. And that is what we are saying: it is a partial oxidation of copper at the graphene flux each; that is what a figure has shown B at each, and at the center, which has been shown over here, it will give a partial oxidation of the copper. And then another point comes at the graphene, where the moisture can be adsorbed. It will give us some sort of splitting of water, and it will give a H and OH bond and then the iron in there. So, this will create more and more chances of corrosion, and then figure D to G has also been shown, and last time we mentioned something like an inversion of the oxygen molecule, and this is what we are going to repeat again. We say that figure D to G is a complete oxidation process, which has been demonstrated.

And in this case, particularly the black dots, or a sphere, and the white sphere, they are representing the carbon, and the red spheres, they are presenting the oxygen. So, this is oxygen, and in this figure D, it has been shown the inversion of oxygen, which means that oxygen is reaching to the atom always in the material and allowing the iron oxide, and this is copper oxide formation. So, what we can say here is that, beginning with graphene vacancies or some sort of impurity, there is a chance of a bond with water because there is humidity in the environment or oxygen. They get chemisorbed, or maybe they make a chemical bond with the graphene, and then they can be absorbed on a surface. What will happen as a result is that there will be a carbonyl group formation, and oxygen will be able to come onto the grains. That has been shown, and in figures E and F, the inversion of the oxygen atom has been shown as a result of the buildup of the oxygen atom. This is an inversion that has been shown over here. And this allows for the oxidation of the copper, and oxygen, as such, is not available on an open surface, but because of the graphene, it is able to find the roots.

So, this is what we have shown: that because of the graphene or graphene impurities, it is allowing copper to get oxidized or partially get oxidized, and that we need to really keep in mind that many times we say the graphene is a very good lubricant with good conductivity and all, but it may also lead to corrosion. Now, in this topic, we are going to place more emphasis on the galvanic series because we were discussing galvanic corrosion, which may be mentioned very clearly in the galvanic material. For galvanic corrosion, we require two materials, and then those materials need to have some sort of difference in their potential. So, that is what we are going to mention again. Here, the galvanic series is a list of the metals or alloys, and those are ranked, but their relative electrochemical nobility, or the reverse of nobility, is reactivity. So, we can give a ranking of the material, whether it is very reactive or least reactive.

If it is the least reactive, then it is a normal material; if it is very reactive, then we will say that it is the most reactive, which means anodic material. And as has been shown over here, the most reactive anodic material is highest in this case. We have kept magnesium, and then comes zinc. That means if there are two metals, zinc and magnesium, magnesium will be sacrificed; it will be the anodic material, and zinc will act as a cathodic material. Now, instead of going with magnesium and zinc, if I make a pair of zinc and aluminum, what will happen? In this case, the aluminum will become cathodic and the zinc will be anodic. So, in one situation, zinc was acting as a cathode; in another situation, zinc was acting as an anode. So, it depends on their relative electrochemical nobility.

So, this is a series now of cadmium and then iron, lead. In this case, what is the meaning of that? If we go with a pair of iron and lead, lead has a lesser chemical activity compared to iron. So, I mean, iron is going to get corrosion, or galvanic corrosion, compared to lead. So, this is a continuation, and then that is why here another example has been shown of a nut and bolt connection. In this case, it has been shown that in the bolt is a base of brass, which has a copper content; as such, another one is a mild steel, which has an iron content. So, we are able to show that this mild steel nut is going through corrosion. You can see the corrosion on the surface itself here.

While the bolt is more or less clean, it does not have it; this acts as a cathode, and the nut acts as an anode. So, it has been shown that the cathode, which is a protected and anode, undergoes corrosion. So, based on this series, we can really choose the right material for the right situation. And one way to demonstrate is something like this, which we have just picked up from one of the references, and the reference has been coated over here. So, in this case, gold and platinum are noble materials; copper and cobalt follow, and then lead, tin, iron, chromium, zinc, and aluminum follow.

However, you are able to see the difference here. Here, we have kept zinc on the more reactive side compared to aluminum. While in this case we are keeping that aluminum is more reactive compared to zinc, the same thing is true for lead and tin. In this case, we have kept lead as more reactive compared to tin. In this case, we have kept lead as a less reactive material compared to tin. So, this indicates very clearly that if there are some sort of experiments to be done, this relative ranking may differ to some extent—not completely, but to some extent.

What is the reason for that? Because the temperature and pH can modify metal reactivity and change the ranking in a series. So, it depends on the environment in which this kind of ranking was done. If we go ahead without really looking at all the parameters, then we make a mistake. So, another word we can say clearly is that this ranking or kind of guidelines, we should not immediately come to the list and then we need to stick to that. There is a quite possible change in a scenario; a change in pH value, a change in temperature, or a or a relative ranking may change a little bit, and then we need to think about which material will get corroded, and based on that, we will choose the right material.

So, let's consider the overall implication here. When metals of differing reactivity come into contact, especially those from a series, galvanic corrosion tends to occur. Initially, this process may not exhibit significant wear or material removal, nor will it show extensive corrosion. However, as the process advances, more cathode formation happens, diminishing the remaining anode, thus accelerating the corrosion process significantly. Initially, all corrosion processes may seem slow, but they exhibit nonlinear progression, potentially leading to rapid failures. It's crucial to keep this in mind as an important aspect to consider.

Now I am trying to show a comparison of the two galvanic series. One article in the literature says this is a quantitative analysis, which they have done on an experimental basis. The other one is Nernst equation-based qualitative analysis or modeling-based analysis, and then you can see the ranking here. In the experiments, researchers discovered that gold is more noble than platinum, whereas the Nernst equation revealed that platinum is more noble than gold. So, if the situation changes, the assumption changes, or there may be a medium change or temperature change, then there is some sort of change in the relative ranking, and that is possible.

And the same thing has been shown in this case as well: aluminum versus zinc. In this case, aluminum is going on a more noble side compared to zinc, while in this case, zinc is on a more noble side compared to aluminum. So, we cannot go, as it is what has been published. We can take a guideline from this, and of course, if there is a Nernst equation, we can go ahead with a solution to the equation, and we can figure out what the relative ranking will be. However, we are not going into detail about that equation or how we solve it.

This is a separate subject, corrosion, and we can discuss those things. However, in the present course, we are not discussing that kind of theoretical modeling. Now, coming to the what we have covered earlier uniform corrosion than we say galvanized corrosion. Now, we are coming to the third category, which is called localized corrosion. And in my previous lecture, I mentioned very clearly in some references that localized corrosion has been mentioned as one category, but in the present course, we want to divide this localized corrosion into two separate categories.

And then what we want to say is that it is pitting corrosion and crevice corrosion. There are two separate categories: pitting corrosion and crevice corrosion. We want to keep two separate categories. Why do we want to do that? That is what I want to explain. We say pitting corrosion means the creation of small localized pits. So, how is it different from a uniform pit? Because in a uniform pit, the complete surface gets corroded. While in this case only the localized pits are getting corrosion, it may be that some surface has a scratch or some sort of mark that only surface that portion is only getting the corroded remaining surface is not getting corroded.

Localized corrosion on a metal surface occurs due to the formation of pits, which despite their small size compared to the overall surface, have the potential to penetrate deeply. Another critical aspect to consider is that while these pits may start small on the surface, they can extend vertically downward, leading to intergranular corrosion (IGC), which is far more detrimental than uniform corrosion. Unlike uniform corrosion, which is easily visible, pitting corrosion may not be readily apparent until it reaches a substantial size or becomes visible. As these pits deepen, the risk of significant harm, including potential structural failures, increases.

Pitting corrosion arises from local chemical or electrochemical processes, such as oxidation, and is characterized by the formation of anodic pits on the metal surface, with the surrounding area acting as a cathode. This disparity in surface area between the anode and cathode accelerates the corrosion rate significantly. Pitting corrosion progresses more rapidly than uniform corrosion and can extend vertically downward through multiple grain boundaries, resulting in substantial damage without early detection.

Detecting pitting corrosion in its early stages is challenging, and once initiated, diagnosis becomes even more difficult compared to uniform corrosion. Pits can evolve from small imperfections into sizable craters, even in materials presumed to be corrosion-resistant.

Crevice corrosion occurs in narrow gaps, such as those between metal surfaces or between metal and non-metal surfaces, where corrosive substances can accumulate, creating a localized environment conducive to corrosion. The absence of oxygen flow prevents passivation, leading to intensified corrosion. The concentration of corrosion media continuously increases within the crevice, promoting electron exchange and corrosion.

Corrosion in crevice areas can lead to significant material degradation. Pitting corrosion, on the other hand, occurs on exposed metal surfaces and is initiated by local chemical or electrochemical processes. While crevice corrosion may remain hidden initially, it can ultimately lead to the formation of visible pits, albeit with delayed detection compared to pitting corrosion.

Pitting corrosion, characterized by small flaws on metal surfaces, can initiate from scratches or surface imperfections. Prevention strategies aim to maintain passivation on metal surfaces, although failure of the passivated layer can lead to accelerated corrosion. Proper detection and mitigation of both pitting and crevice corrosion are essential to prevent material degradation and structural compromise.

Maybe again there is some sort of scratch on that, or maybe there is some sort of tension, and the tension that this coating fills exposes a small patch. So, one small patch is sufficient to again start this kind of corrosion, and if the corrosive media is sufficient or maybe there is a formation of cells, then the passivation layer, which is initially the good protective layer, is started because of some sort of failure in a coating, and then before it really refurbishes, before it is self-healed, pitting is started, and then in that case of the pitting when it is started, it cannot be self-healed. So, this is what we say: there is a flaw; there is a possibility that there was a passivated film and then it broke; and in the in the third very silent case, we say if there is a passivated film, it is also not broken at all. So the situation is in our favor as such. However, there is a possibility of pit creation; there is a possibility of nucleation; and how does the nucleation come about? It will be basically the formation of the iron, that is, the metal starts creating some sort of vacancy, and that is what has been mentioned here: there is a nucleation, and once a nucleation starts some sort of subsequent process will be the growth of the pit, which is what we call a propagation.

Even if the initial protective film on the metal surface remains intact, there is still a possibility of pit formation and corrosion. This process can begin with nucleation, which may be slow and take many hours. Once nucleation starts, it leads to propagation. Initially, the metal surface may appear unharmed during what is known as the induction period. This induction period is the time needed for vacancies in the oxide layer to grow to a critical size, which varies depending on conditions such as tensile load.

Pit formation might begin from scratches or breaks in the passivated film, or from nucleation below the passivated layer. Once a pit starts forming, subsequent pits can develop more rapidly. For example, if the first pit takes 1000 hours to form, the next one might take much less time, especially in nearby areas.

The pit itself acts as an anode while the surrounding metal surface acts as a cathode, especially if an electrolyte is present in the pit. Since the anode (the pit) is much smaller than the cathode (the surrounding surface), the corrosion rate increases rapidly. This leads to significant subsurface corrosion, even if the pit aperture remains relatively small on the surface.

As pitting corrosion progresses, tiny pits or cavities begin to appear on the metal surface. These pits can deepen and expand, causing substantial damage. For instance, a pit might start small but grow significantly larger beneath the surface.

Pitting corrosion involves two main stages: nucleation and propagation. Initially, a protective oxide layer forms on the metal surface. However, cation formation or diffusion can lead to the metal losing electrons to the surrounding media, creating vacancies. As these vacancies grow, nucleation occurs, eventually leading to pit formation once the electrochemical potential of the metal surface falls below a specific threshold.

Overall, pitting corrosion starts with the formation of small pits that can deepen and expand, leading to considerable subsurface damage even if the surface aperture appears small. Proper detection and prevention are crucial to mitigating this type of corrosion.

If the metal we are using has an electrochemical potential below a specific threshold, what is that specific threshold? It depends on the different situations, and sometimes you say the pitting potential in that situation, then the metal cation diffusion will start from the oxide metal interface to the oxide outer surface that is shown over here, from the inside surface to the outside surface of the oxide. And then, when the void grows to a critical size, as we mentioned in the previous slide, it can be a few microns; it can depend on the size, or when the condition is critical as a result of the accumulation of vacancy oxide film in a specific area. So if there is a vacancy and it is continuously increasing, then there is a possibility of cracking, or it may be the failure of the oxide film itself, and that will act as an initiation for the crack formation, and that has been shown in a bigger way right here. Since we have removed the top surface and the oxide, we are able to show that the oxide is broken or something like that. The enlarged void before pit formation has been shown over here. Now this is in better form has been shown in the pit formation has been shown in this.

So there is a nucleation, there is some sort of anionic formation, or iron start formation starts, metal ion starts forming, and then it is all there is a possibility of vacancies, and that is creating this manner. Now this is a bigger view where we are showing complete pitting corrosion. We say pitting corrosion forms a cathodic region on the top surface. Therefore, the entire surface I've depicted is a cathode surface, whereas this particular pit functions as an anode. So pitting corrosion forms a cathodic region on the top of the pit and an anode region at the bottom.

So, this illustration shows how the entire surface can act as an anode, gradually enlarging over time. The lack of sufficient oxygen to form a protective layer, combined with the presence of metal ions and electrolytes, enhances the corrosion process. As time passes and the number of cycles increases, the pit size can grow.

Sometimes, this enlargement occurs under AC current, where the fluctuations can significantly increase pit size. Although this isn't covered here, we will discuss an example of pit formation under AC current in lecture 11.

Crevice corrosion, in my view, is one of the most dangerous types of corrosion. It often occurs in areas where welding or joining of metal surfaces leaves small gaps or voids, either through holes or blind holes. These gaps are sufficient to create crevices where corrosion can develop.

Crevice corrosion forms in tiny voids between interacting metals, which can result from various joining processes such as welding, riveting, cascading, threading, or coating. Even a small gap in these processes can lead to crevice corrosion.

This type of corrosion happens when a metal surface is exposed to a corrosive environment, causing a difference in the concentration of corrosive substances within the crevice compared to the surrounding area. The stagnation in the crevice allows the concentration of corrosive substances to increase continuously, accelerating the corrosion. Outside surfaces might not corrode, but within the crevice, the concentration of electrolytes and metal ions will keep changing, promoting further corrosion.

So, it is not moving at all. So, in this case, concentration will continuously change, and then there will be a possibility of accelerated corrosion in that region as such. So we can see that the difference in concentration causes the accelerated corrosion because it produces an electrochemical cell. So I can say this is an electrochemical cell; this is acting as an anode; this is acting as a cathode. So an electrochemical cell is acting as an electrochemical cell as such, and that too within a fissure, within a crack, or within a deep crack itself. The reduction process occurs at the cathode, which is what has been mentioned on the surface, which matches a metal exterior or bulk in this example.

So the outside surface in this case and this complete structure can act as a cathode, and this small hole and then deeper inside can act as an anode. This difference in electrochemical activity causes the passage of electron ions within a crack, which promotes the corrosion that has been mentioned over here. Now one of the major issues is that it is difficult to detect in the small area where we cannot put a sensor; we cannot really find out so easily how this kind of corrosion is progressing and moving at a much faster pace or accelerated rate. So we require either an indirect method or a non-destructive testing method to figure out what is really happening, which may turn out to be costly. But if we are able to choose the right materials and we are able to fill all the gaps perfectly, and there is no possibility of electrolyte going there, moisture going there, or acid going there, staining or becoming stagnant there, then chances will come down significantly.

Many times, we fill those gaps with normal glue, and that will also help. However, if we make the right decision, this kind of failure can be avoided. Now we can see that this crevice corrosion is frequently difficult to detect and proceed with quickly because the corrosion produces a concentrated solution in a limited space, worsening the condition of the corrosion itself. Accumulation of chlorides—that is what we say—there is some sort of high acidity in nature. So, some sort of a chloride or other corrosive substance can speed up the corrosion process.

Corrosion can eventually cause metal penetration, perhaps a catastrophic failure. There is a possibility, however, that, as per our knowledge, this crevice will turn out to be a pit formation. So we will have some sort of detection method, and we will be able to figure out what is going to happen there. So to prevent crevice corrosion, careful design considerations are required, such as decreasing the geometry of the of the crevice in such a way that it should not happen. We need to make perfect joints, or maybe the perfect matching as such, so that there should not be this kind of gap, and then there should not be crevices remaining on the formation of crevice holes or geometry there at all. Then we need to go ahead with eliminating all the stagnant spots there should not be any liquid in there or maybe the chemical there, the strength at one location for very long time.

And finally, we say that we can use corrosion-resistant materials. This is a kind of protection device. We can think about protective coatings, sealants, and corrosion inhibitors in the same way that we discussed them in the previous lecture. So, these are the physical barriers that will stop chemical activities, the protective coating is a possible sealant, and corrosion inhibitors can also be utilized, particularly the corrosion inhibitors in engine oil and gear oils. The sealing sealant has been used in most of the seals because, as we know, the seals are made of elastoplastic or viscoelastic materials. They will remain in some shape for some time, but after some time they may deform, and then there is a possibility of an air gap getting generated. If you want to really seal that, then life can be extended. Now we will just consider the one case study that is related to crevice corrosion, and then we are referring to the one paper; unfortunately, in this paper they are using the super stainless-steel word, and supper they have used super.

I do not know whether this is this is the type of error or if they want to specialize this word as such a SUPER. So in this particular lecture, I am going ahead with the SUPER stainless steel. I am not going with the double P in this case. So super stainless-steel material is what we are talking about, and what is that super stainless-steel material? You see, it has outstanding corrosion resistance. Why outstanding? It has a very high nickel percentage, a very high chromium percentage, and a high molybdenum process. So, all three materials are abundant, or maybe more than sufficient, which is really or is available in other stainless-steel materials. If you look at molybdenum itself, it is 4%.

Now, let's talk about the nickel content, which is 25%, and the chromium content, which is 20%. These high concentrations of both elements are why this material is referred to as "super stainless steel." While stainless steel is already known for its corrosion resistance, this particular composition offers even greater protection.

The question arises: will this super corrosion-resistant material corrode at all? To answer this, experiments need to be conducted according to ASTM standards. These well-established standards dictate how corrosion tests should be performed, specifying the type of workpiece, the experimental procedures, and the frequency of testing.

In theory, we can drive some relation, we can give a ranking, or we can have some understanding, but in the actual case, parameters may differ to some extent, and then whatever we take from one piece of literature may not really give us the right results or the right understanding. So, that is why I am just referring to this paper, and this is, as I say, the super stainless steel; it should be super resistant to all kinds of corrosion, and we want to test it now as per ASTM G 78. They have made special testing for the crevice forming assembly to find out the corrosion resistance of crevice corrosion, and then they mention how to go ahead with the assembly, and then they have also mentioned 20 plateaus to be made on a polyethylene material, which has been shown over here. This is a 7 mm, and then the slots have also been shown very clearly as such, and then the angle of the plateau has also been shown.

Here we have a material that needs to be tested. The dimensions are 30 x 30 x 6 mm with a central hole of 7 mm to accommodate a platinum bolt. This setup is designed to examine crevice formation in a stainless steel specimen. The complete assembly is integrated with a copper wire, and it includes the stainless steel specimen and an inert material, likely polyethylene, that forms the crevice.

The assembly is exposed to a corrosive environment for a specified period, typically 2 hours, with an initial 30-minute exposure to the environment. The level of crevice corrosion is assessed both visually and quantitatively. Visual inspection can detect corrosion immediately, but the authors also used advanced techniques like ACM to identify the type and extent of corrosion.

The experimental setup uses an electrolyte, often artificial seawater with double the normal concentration to accelerate wear testing. The setup includes three electrodes as per ASTM G61 standards: a working electrode (the stainless steel specimen assembly), a reference electrode (saturated calomel electrode), and a platinum sheet electrode. The assembly is kept in the electrolyte for 30 minutes, and a cyclic potentiometer polarization test is conducted at 17°C.

This setup demonstrates how the crevice corrosion site is analyzed. The site is divided into three parts: a zoomed-in view of a 200 µm section using EDX, which reveals a passive layer on the surface containing elements like molybdenum, chromium, and nickel. This passive layer acts as a protective barrier. Additionally, mildly affected sections and severely attacked regions are identified, showing that even super stainless steel can corrode if there are gaps, irregularities, or discontinuities.

The experiment emphasizes the importance of not just the material but also the assembly and the conditions under which it is used. A thin oxide layer made of elements like iron, chromium, molybdenum, and nickel forms a protective cover structure, as shown in the EDX analysis. Proper design and consideration of these factors are crucial to preventing corrosion. The study also notes that crevice corrosion can lead to pitting corrosion, with pits larger than 50 µm increasing the likelihood of further surface damage.

So, it is leading to pitting corrosion. So, if this is the hidden or what is it, the corrosion that was not visible finally, it will come on the surface and we are able to see that corrosion, and then it will act like a pitting corrosion, and we need to take appropriate care based on that. Now, last in a series, because we have covered four types of corrosion, we started with uniform corrosion, galvanic corrosion, then we say the two types of local corrosion: one is pitting corrosion, one is crevice corrosion, and the last one is stress corrosion, stress corrosion cracking, and in short, we say the SCC. So, stress corrosion cracking is very common in all kinds of mechanical systems. What is really required is a material; it requires a corrosive environment and tensile stress. If any of this is missing, then corrosion will not happen naturally. The material will be essential, and we need to keep it in the area. If we are able to prevent the corrosion environment or tensile loading, then this kind of corrosion will not occur. However, even if we keep saying compressive stress, it will be in one direction, and in the other direction, it will lead to tensile stress.

Stress corrosion cracking (SCC) occurs when a material, such as titanium alloy, steel, or stainless steel, is exposed to tensile stress and a corrosive environment. Tensile stress can arise from increased temperature or residual stresses from manufacturing processes like assembly, heat treatment, or quenching. Residual stresses, often tensile, may remain even after processes like tempering. Proper annealing is necessary to prevent these stresses, as they can lead to failure.

For SCC to occur, three elements are needed: the material, tensile stress, and a corrosive medium (e.g., saline water, acidic or alkaline environments, or corrosive gases). SCC can lead to significant system failures, as seen in the example of a completely broken chain. Under tensile loading, cracks form and act as anodes, while the surrounding surface acts as a cathode. The crack area, being smaller, facilitates ion formation and concentration of the electrolyte, accelerating corrosion.

Water can infiltrate cracks, creating cells where the anode area is much smaller than the cathode area, leading to rapid ion increase under tension. Small surface defects can nucleate SCC. Essentially, SCC happens when a material fractures under combined tensile stress and corrosive conditions. Testing for SCC involves subjecting a specimen to a corrosive environment while applying slow, constant tensile stress or strain rate, following standardized procedures to assess material resistance and expected service life.

It's crucial to understand and adhere to standards to determine material resistance to SCC. Materials subjected to residual or other stresses, coupled with corrosion, can experience rapid failure. For example, in a high-temperature environment (155°C) with magnesium, stress corrosion cracking can occur. Understanding these factors helps in designing materials and assemblies to withstand such conditions and extend their service life.

Magnesium is very weak, and maybe on the noble side, it has a very high chemical reactivity. So, this magnesium chloride solution is basically the corrosion environment of austenite stainless steel. We know the austenite stainless steel with only one kind of phase will be there, but we wanted to test whether this kind of material is going to be foolproof against corrosion resistance or not. So, what we are saying is that we are going to place emphasis on stress corrosion cracking. We are keeping a high temperature of 155°C and the corrosion environment as a magnesium chloride solution, and then we want to test stainless steel to form the austenite stainless steel. So, this is what we picked up: this is also from the Wu et al. (2018) paper. This paper and you can see here stainless steel, particularly the 20% , has been given something like chromium.

This is 20% chromium, and 0 is being given as nickel. So, nickel and chromium have very high resistance to corrosion, which is why we are using this kind of material. And now we are using the word austenite in stainless steel because it has ferrite and austenite, and we know the ferrite can really prevent crack growth. If there is a crack, if you provide a some sort of ferrite structure, or maybe the phase will stop, it will put a barrier around the crack. So, it is a very good material to reduce or minimize cracking, and that is why we wanted to test this material, and that is where they say whatever the properties of the material whether they are clearly sustained under stress conditions or particularly tensile stress conditions. We have used the electric arc and argon oxygen decarburization melting process in the furnace to manufacture this type of stainless steel material.

So, it does not get easy oxygen, and it should not get the contaminated material. And then in this case, particularly, the whole thing has been done, and then this solution treatment has been done at 1180°C , particularly for a duration of 8 hours. So, after doing this again, they have come up with another treatment. What is that treatment as such? And then they made three samples, A1, A2, and A3, and then they got material, and then after that, they did the test as well.

So, they have used complete ASTM standards. So, G 36 specifies what should be A1, what should be A2, what should be A3, and this is the standard they have followed. And then, in this case, in all three cases, they have changed the feed rate to 60, 90, and 150, while the spindle speed has been kept at the at the same 450 rpm and the depth of the cut has been kept at 0.1 mm. The same thing, and then to conduct the test and observe the crack at any cross section, they used epoxy resin. They embedded a specimen of epoxy resin. And then, after doing this, they follow the standard as per this one, you say that, they grounded using the silicon carbide paper, which we sometimes call the Amelie paper kind of thing.

They polished the surface using silicon carbide paper and then used 1.5 mm diamond powder for the test. To put it another way, they milled the specimen according to standards and labeled them as A1, A2, and A3. They annealed these specimens at three different temperatures: 300°C, 450°C, and 600°C. The annealing process lasted for about three hours, after which the specimens were cooled to room temperature in the furnace under an inert argon gas atmosphere to conduct the SCC test.

For the SCC test, the specimens were exposed to boiling magnesium chloride at a temperature of 155°C, with an accuracy of ±1°C. The experiment was conducted for two hours, and the crack density was determined by measuring the length of cracks in a specified area.

So, this is the final figure, which they have shown over here. You can see the depth of cut in the first case, and then the 60 mm in 90 mm per minute, and the other 150 mm per minute, and then this is an A1. As we see, they receive the material as it is; they have not annealed it. In this case, annealing has been done at 300°C, 450°C, and 600°C . And they have observed them as A1, A2, and A3, and all three specimens, and what has been mentioned here is something like, and then the feed rate was 60, 90, and 150. So, as the feed rate is increasing, they find more and more cracks, and we know that as the feed rate increases, the loading will increase indirectly, and then as they are going for a higher temperature of annealing the 600, 600, 600, they find that the cracks are completely disappearing at a 600. So, they say that if you want to avoid this kind of stress corrosion cracking in the situation, try to do annealing at 600°C that will cause a lesser number of cracks, or almost negligible cracks, irrespective of the kind of and the feed rate with the 150m/minute . We also did not find any substantial cracks in this case. So, that is why we say the crack morphology of the milled A1, A3 specimen has been shown here. Annealing at 300°C was ineffective to prevent any crack initiation or may be causing any. This is because crack initiation is dominating, while keeping the annealing temperature at 600°C is avoiding the kind of cracks.

Therefore, they emphasize that it's not only the material but also the manufacturing process that matters. Earlier, we mentioned the importance of proper assembly without gaps, but here, the manufacturing process is given significant emphasis.

In summary, we need to consider the material, manufacturing, and assembly together to prevent corrosion. No single factor—material, assembly, or manufacturing—can prevent corrosion on its own. A perfect combination of all these elements is required to achieve the right solution and parameters.

With this, we are concluding the topic of corrosion. In lecture 11, we will cover the synergistic combination of degradation mechanisms, hoping to integrate all the concepts learned in the past nine lectures and present a few case studies to explain these phenomena properly.

Thank you for your attention.